BATSE Observations of Cygnus X-1

J. C. Ling, Wm. A. Wheaton, and R. T. Skelton*
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

B. A. Harmon and G. J. Fishman
NASA/Marshall Space Flight Center, Huntsville, AL 35812

W. S. Paciesas
University of Alabama in Huntsville, Huntsville, AL 35899

ABSTRACT

We report preliminary results of ~65 days of BATSE Earth-occultation observations of the low energy gamma-ray (20 keV - 1.8 MeV) emission of Cygnus X-1 covering the period from 23 April to 27 June 1991. Cygnus X-1 underwent two transitions in this period. The 45-140 keV flux was first observed between the γ_1 and γ_2 levels (Ling et al. 1987) from 23 April to 14 May. The source began a transition to γ_1 on 14 May and stayed near this level from 19 to 29 May, and then moved toward γ_2 and remained at approximately this level from 10 to 27 June. Both γ_1 (19-29 May) and γ_2 (10 -27 June) spectra observed by BATSE can be best characterized by the Comptonized model with temperature of 67 keV and 62 keV, respectively, and optical depth of ~2. There was no evidence for any broad spectral feature near 1 MeV seen previously by several satellite and balloon experiments. A composite Cygnus X-1 spectrum observed by BATSE and COMPTEL in Viewing Period 2 (31 May -7 June) suggests that a power-law with index of ~3.5 may best characterize the spectrum from 200 keV to several MeV.

INTRODUCTION

Cygnus X-1 is one of the strongest celestial low-energy gamma-ray (0.02 - few MeV) sources known to date. It has displayed long-term temporal and spectral variability which includes (1) hard x-ray (45 -140 keV) flux variation among several levels (Ling et al. 1987; Ling 1988) with time scale ranging from days to months, (2) episodic broad spectral features in the 0.5- few MeV region which have been interpreted as evidence for relativistic pair plasma in the accretion disk (Nolan & Matteson 1983; Ling et al. 1987; McConnell et al. 1989; Liang & Dermer 1988), and (3) a possible narrow 0.511 keV annihilation line feature correlated with the broad MeV feature (Ling & Wheaton, 1989) providing further supporting evidence for positron-electron pairs produced in the system. Several issues related to these observations remain unresolved. For example, what is the mechanism driving the long-term flux variation? Is there a pattern which may help explaining the physics responsible for such variability? Is the broad MeV feature real? If so, it needs to be confirmed. What is the mechanism responsible for the formation of such a pair plasma?

The Large Area Detectors (LAD's) of the BATSE experiment onboard the Compton Gamma-Ray Observatory (CGRO) are ideally suited to answer many of these questions. They have the capability to provide nearly uninterrupted monitoring of cosmic sources with unprecedented sensitivity using the Earth as an occulter for modulating the source signals (Harmon et al. 1992; Skelton et al. 1992). We have been monitoring Cygnus X-1 since

* National Academy of Sciences/National Research Council Senior Resident Research Associate

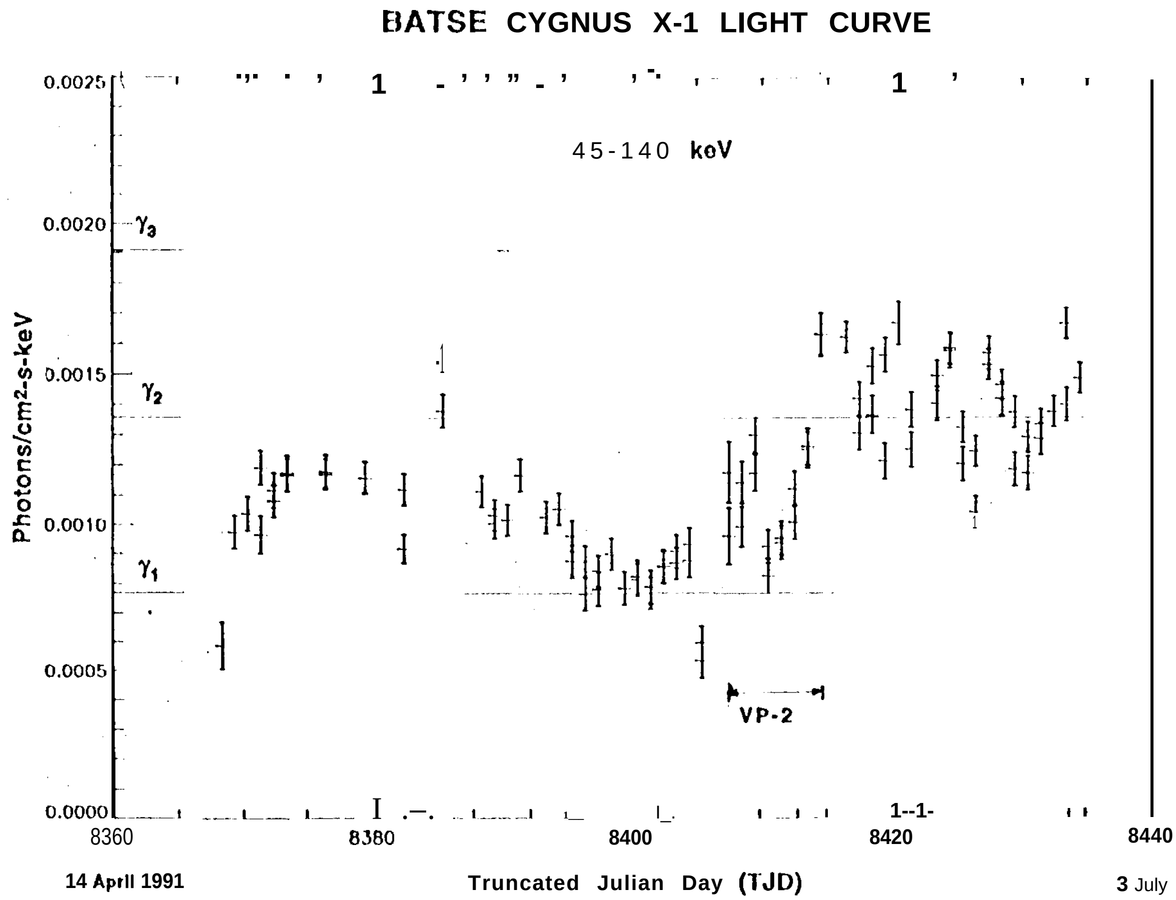

Figure 1. The Cygnus X-1 light curve in the 45-140 keV energy band. Two data points are shown for each day, corresponding to measurements made by different LAD's. The uncertainties include both statistical and systematic contributions summed in quadrature.

launch using MSFC Mission OPerationS (MOPS) anal ysis package (Harmon et al. 1992), and have found that the source made a number of transitions between the γ_1 and γ_2 levels during the first two and half years of the CGRO mission (Harmon et al. 1993a,b). Most of these data are currently being analyzed in detail using a new JPL "Enhanced" BATSE Occultation Package (EBOP) (Skelton et al. 1993, these Proceedings). EBOP is designed to improve the sensitivity of the analysis by using much more data to reduce statistical errors, together with detailed background modeling to control systematic error. In this paper, we present evidence for temporal and spectral variations associated with the first γ_1-γ_2 transition observed in June of 1991. These data were anal yzed using primarily EBOP Version 1.(1. As EBOP continues to improve in the months ahead, we expect these results to improve. Our present results should thus be considered somewhat preliminary. Improved results will be submitted for publication at a later date.

RESULTS

Flux Variations. Figure 1 shows the 45- 140 keV light curve measured by BATSE from 23 April (TJD 8369) to 27 June (TJD 8434) of 1991. For the first 20 days in this

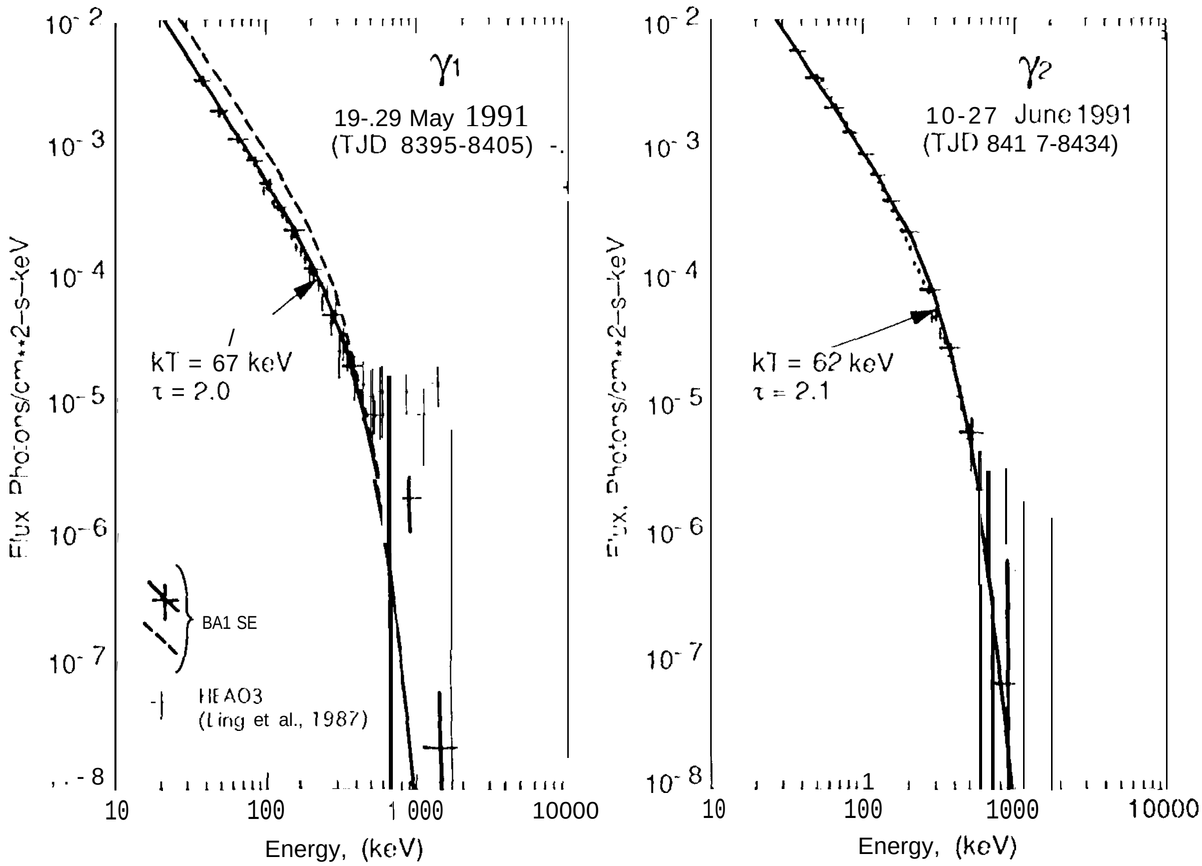

Figure 2. The overall γ_1 and γ_2 spectra observed by BATSE (bold lines) agree well with those of HEAO 3 (Ling et al. 1987; thin dots/lines), the only discrepancy being the lack of the enhanced MeV feature in the γ_1 spectrum (2a). The γ_1 spectrum is harder than γ_2 spectrum (Fig. 2b, shown as a dashed line in 2a) and intersects the latter at a few hundred keV.

period, except for one-day fluctuations. We found the source generally at a level between γ_1 and γ_2. However, starting at ~TJD 8390 (14 May), the flux began to drop and reached the γ_1 level within a few days. It stayed at this level for approximately ten days (TJD 8395-8405) before ramping up toward γ_2 where it remained from TJD 8417 to 8434. The two data points shown for each day correspond to measurements made by two different LADs. The overall pattern of the temporal variability was therefore consistently and independently observed by two LADs. The uncertainty associated with each datum includes contributions from statistical and estimated systematic effects, summed in quadrature. The systematic errors dominate the statistical errors in this energy band by approximately a factor of 4 for this analysis (Skelton et al., 1993, these Proceedings). Their magnitudes have been estimated based on the consistency of the daily fluxes measured by two detectors over a period of ~70 days. While no rigorous treatment of the systematic error is possible, we believe the quoted errors to be conservative. As our analysis method continues to be improved and refined, we hope to reduce the systematic contribution.

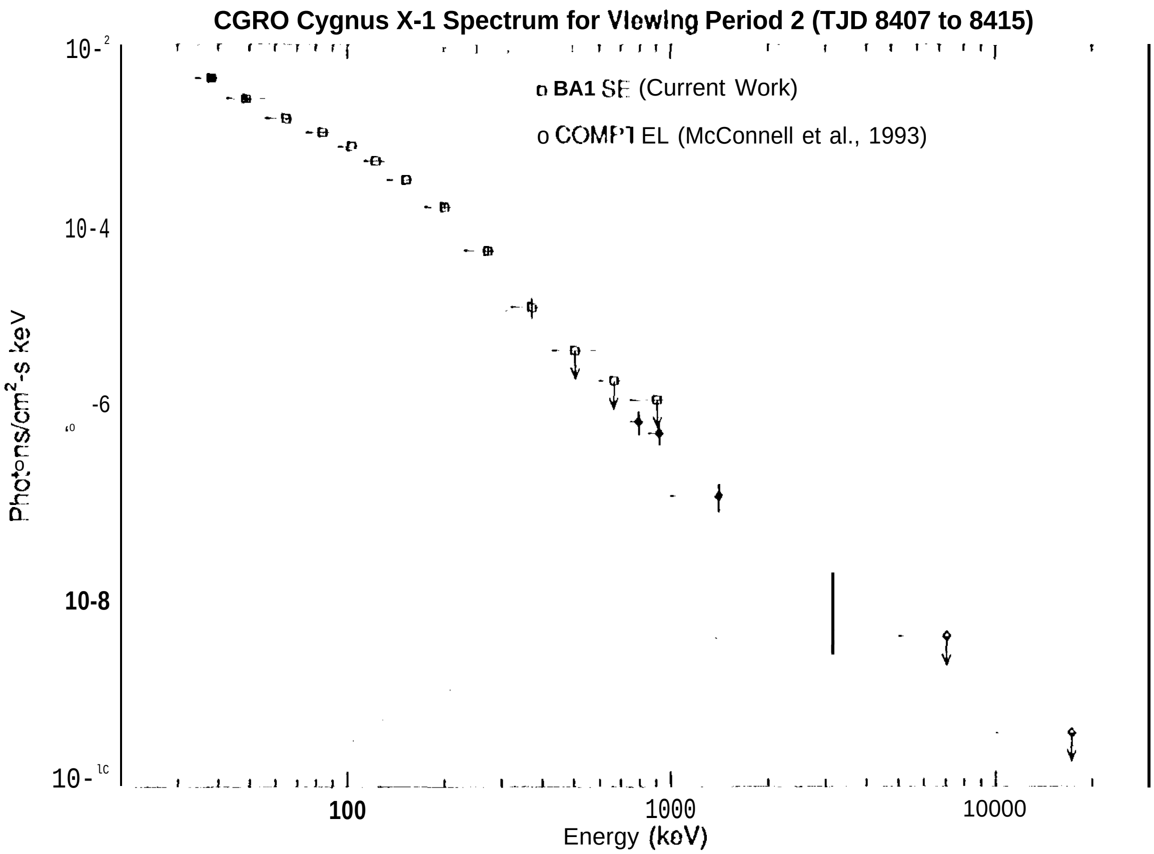

Figure 3. The composite Cygnus X-1 spectrum measured by BATSE and COMPTEL consists possibly of two components: a Comptonized component in the 20-200 keV range followed by a power law extending to several MeV.

Spectral Variations. Figure 2 shows the time-averaged spectra measured during the γ_1 (TJD 8395-8405) and the γ_2 (TJD 8417-8434) periods, respectively. The solid lines are the best-fit Comptonized spectra (Sunyaev & Titarchuk 1980) with $kT = 67$ keV and $\tau = 2.0$ for the γ_1 spectrum, and $kT = 62$ keV and $\tau = 2.1$ for the γ_2 spectrum. We find no evidence for enhanced MeV emission associated with either the γ_1 spectrum as reported by Ling et al. (1987) or the γ_2 spectrum, suggesting that such MeV features may be independent of the hard x-ray states. The γ_2 spectrum (Figure 2b) is softer than the γ_1 spectrum and intersects the latter at around a few hundred keV, consistent with that observed by HEAO-3. Except for the lack of evidence for the MeV feature, both the γ_1 and γ_2 spectra observed by BATSE agree very well with those measured by HEAO 3 in 1979-1980. Figure 3 shows a composite BATSE and COMPTEL (McConnell et al. 1993) spectrum for CGRO Viewing Period #2 (VP-2, TJD 8407-8415). The two spectra are quite consistent in regions where they overlap. It is interesting to note that contrary to our standard view of the Cygnus X-1 spectrum which has typically a Comptonized shape with a sharp cut-off above 300-400 keV, this composite spectrum seems to have two components: a Comptonized component in the 20-200 keV region followed by a power-law, with index of -3.s, extending to several MeV.

CONCLUSION

Cygnus X-1 was observcd to undergo dramatic changes in 1991-1993. Most of these data, specificall y those after July 1991, arc currently being analyzed using EBOP and these results will bc published at a later date. Wc report here preliminary results of the first -65 days of observations covering the period from 23 April to 27 June 1991 using EBOP-Version 1.0. During this period, Cygnus X-1 was near both the γ_1 and γ_2 levels for -10 days and 17 days, respectively. The transition from γ_1 to y_2 took about 10 days. Except for the absence of the broad McV feature in the γ_1 spectrum which was observed by 1 IEAO 3 in 1979, both γ_1 and y_2 spectra agree very well with those observed by HEAO 3. A composite B ATSE and COMPTEL spectrum observed in Viewing Period #2 indicates that the source spectrum may bc characterized by a Comptonized component in the 20-200 keV range followed by a power law extending to several McV.

ACKNOWLEDGMENT

Wc wish to thank Dr. B. Rubin for his assistance in cross calibrating the MOPS and the EBOP results measured by individual LAD and confirming that the two methods produce consistent results. Wc also wish to thank Dr. W. Mahoney for his valuable comments of this manuscript, and R. Radocinski and N. F. Ling for the.ir contributions to the development of the EBOP. Two Caltech Summer Undergraduate Research Fellowship students, K, Polito and R. Esquivel, contributed to the data reduction and analysis of these results. The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology under contract to the National Aeronautics and Space Administration.

REFERENCES

Harmon, B. A. et al., 1992, AIP 280, 314
Harmon, B. A. et al., 1993a, IAU Circular 5813
Harmon, B. A. et al., 1993b, IAU Circular 5881
Liang, E. P. & Dermer, C., 1988, ApJ, 325,139
Ling, J. C. et al., 1987, ApJ, 321, L117
Ling, J. C., 1988, Nut]. Spec. of Astroph. Sources Workshop Proceedings, AIP 170, 315
Ling, J. C. & Wheaton, Wm. A., 1989, ApJ, 343, L57
McConnell, M. et al., 1989, ApJ, 343,317
McConnell, M. et al., 1993, preprint submitted to ApJ
Nolan, P. & Matteson, J. L., 1983, ApJ, 265, 389
Skelton, "I'. A. et al., 1992, AIP 280, 1189
Sunyaev, R. A., & Titarchuk, L. G., 1980, A&A, 86, 121